Electron Density Measurements Using USPR

FUSION Diagnostics Program Review (Virtual)
March 5, 2021

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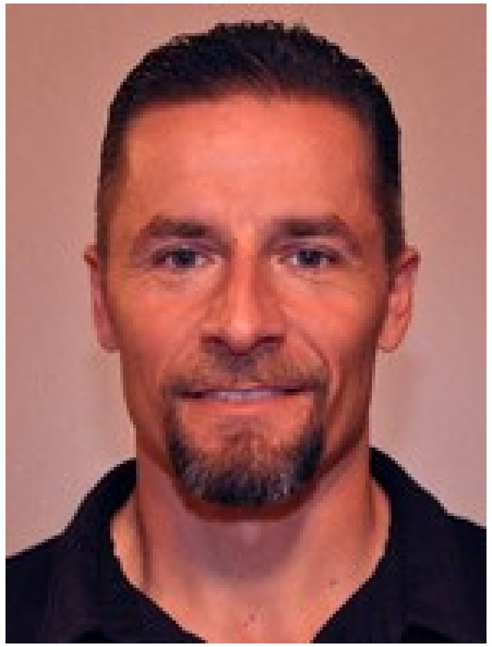
C.W. Domier, University of California at Davis

Team members and roles

Neville C. Luhmann, Jr.
Distinguished Professor
Overall project management

Calvin W. Domier
Project Scientist
Fabrication, character-ization, installation and commissioning

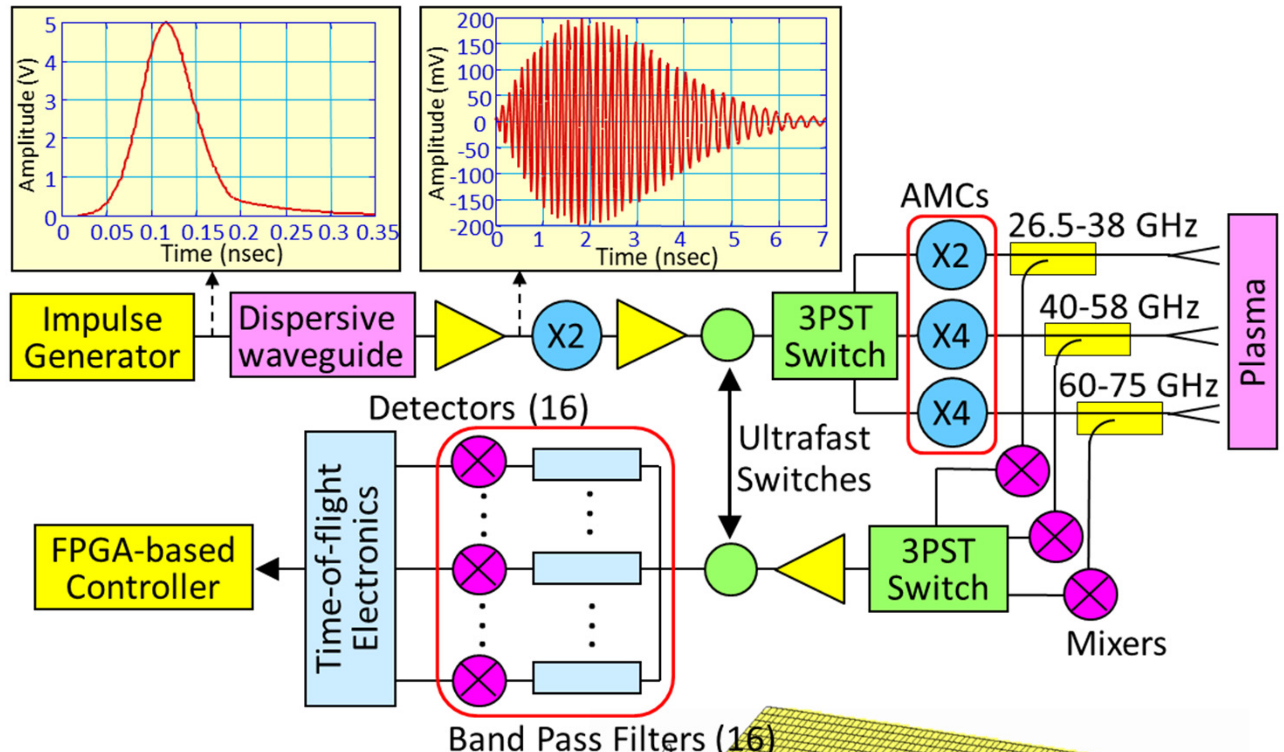


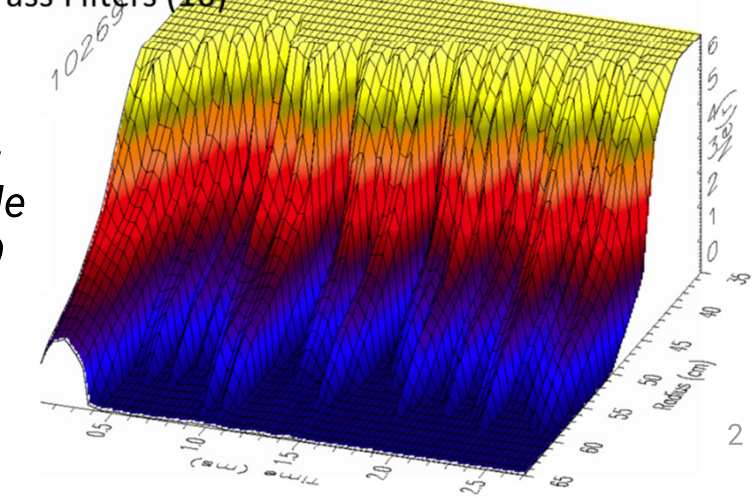
Jon Dannenberg
Development Engineer
Aid in designing and fabricating port interfaces devices

Logan Himes
Development Engineer
Aid in diagnostic installation on ARPA-E devices

Ultrashort Pulse Reflectometry (USPR) Diagnostic Overview

- Ultrashort Pulse Reflectometry (USPR) is a pulsed radar technique utilizing ultrashort (~few nsec) frequency chirps
- Reflected waveforms are split into multiple frequencies; time-of-flight measurements at each frequency are inverted to generate electron density profiles with high time (<10 μsec) and spatial (< 10 mm) resolution
- Monostatic (same antennas used for transmit and receive) configuration to minimize diagnostic footprint
- System targeted to electron densities in the range of $0.9 – 6.5 \times 10^{13}$ cm^{-3}; extendable down to 0.7×10^{12} cm^{-3} or up to 1×10^{14} cm^{-3}





USPR-generated time-resolved density profile for SSPX shot #10269

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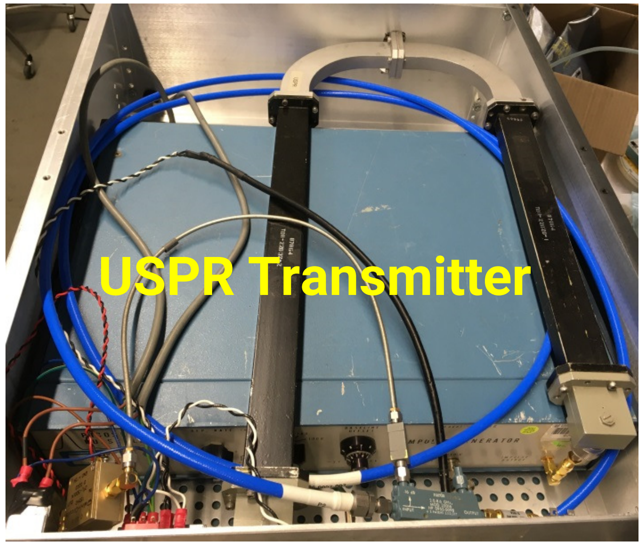
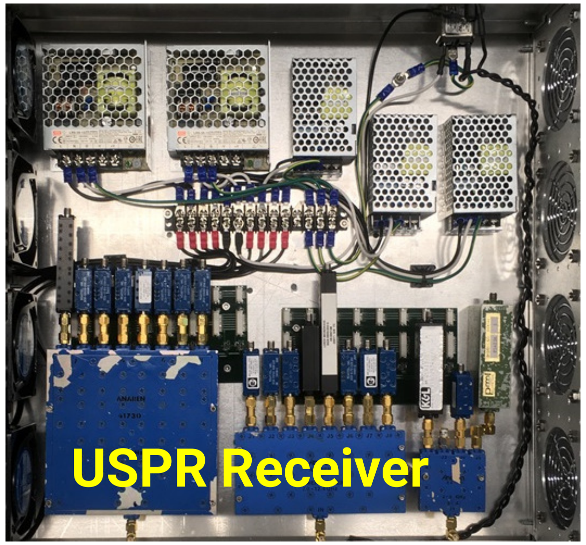
USPR is a Compact, Highly Portable Density Profile Diagnostic

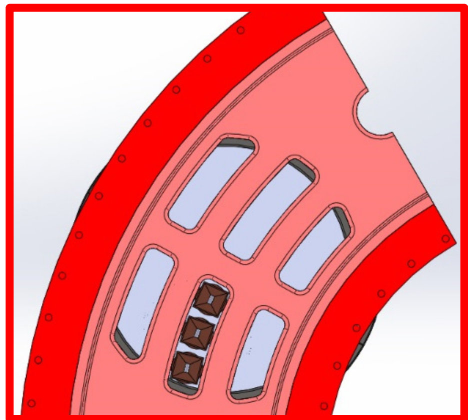


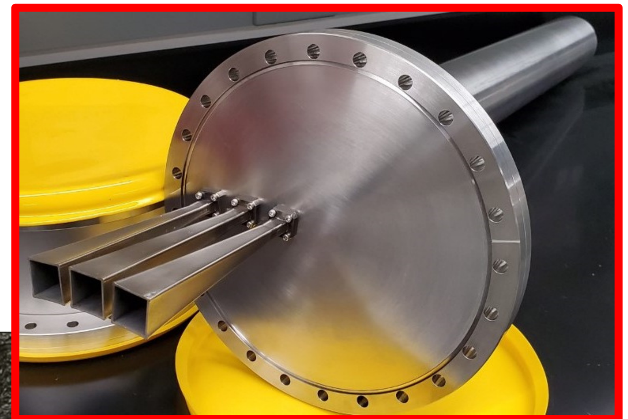


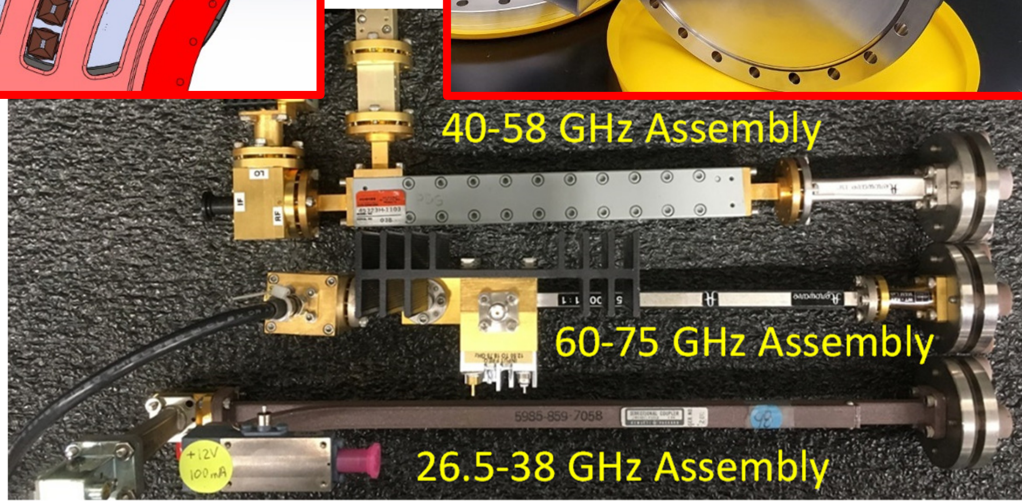
- USPR transmitter and receiver are arranged in compact rack-mount enclosure boxes
- The transmitter and receiver connect to mm-wave assemblies (placed close to the vacuum vessel) via low-loss coaxial cables whose lengths (6 – 20 feet) can be tailored to each plasma device
- Monostatic (same antenna for transmit and receive) minimizes the diagnostic footprint on the device

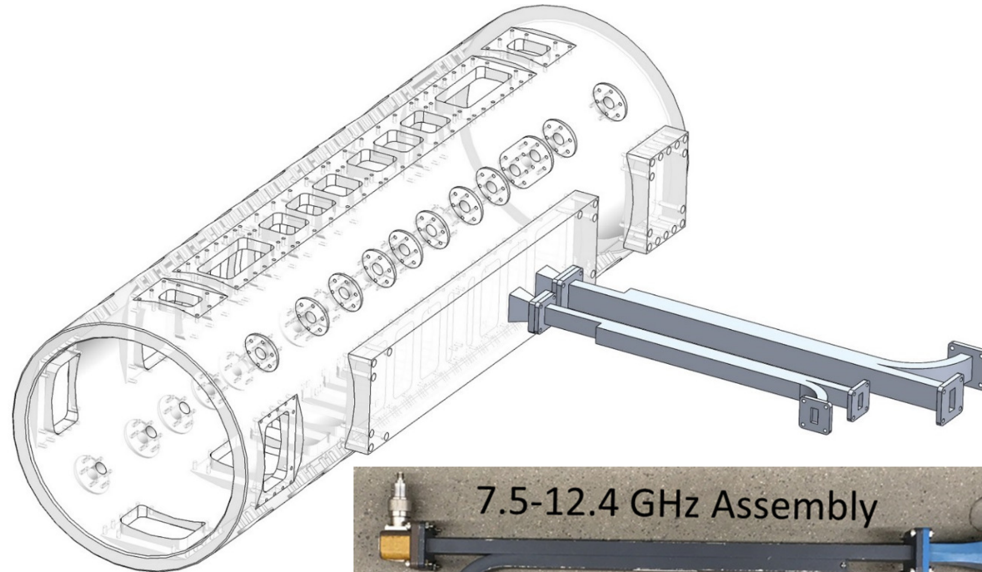
- Self-contained data acquisition and system control using a field-programmable gate array (FPGA)
- Low data load (16 Msample/sec), allowing both pre- and post-analysis data to be easily stored
- FPGA programmed not only to acquire data but also to invert time-of-flight data into time-resolved electron density profiles
- System calibration performed in the laboratory prior to installation – no on-site calibration required

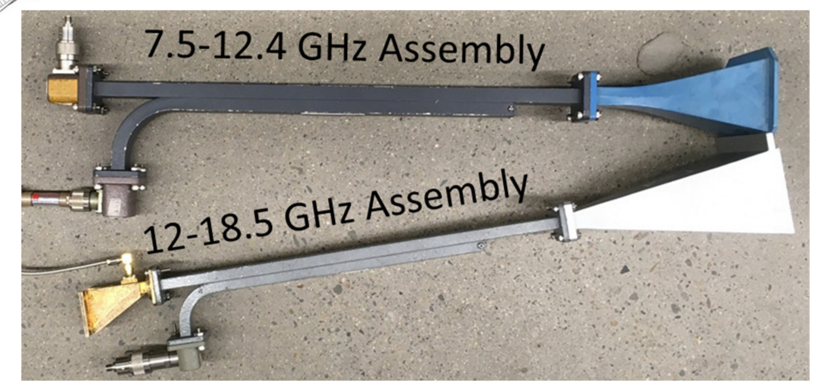
USPR Diagnostic to be Employed on HIT-SIU and PFRC







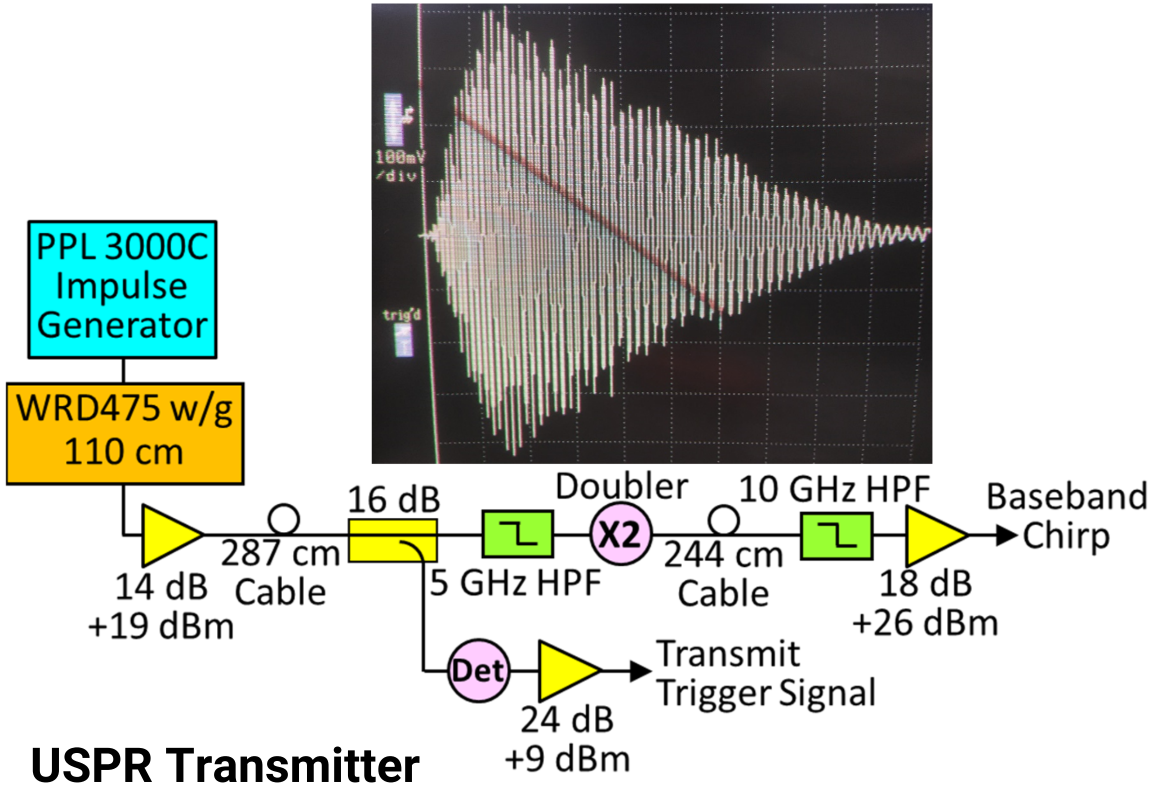




- Three mm-wave band assemblies will be employed on the HIT-SIU spheromak, spanning 26.5 to 75 GHz
- Each horn views the plasma through in-vacuum louvres, with mm-wave assemblies connected through vacuum windows attached to a 36 inch length of waveguide

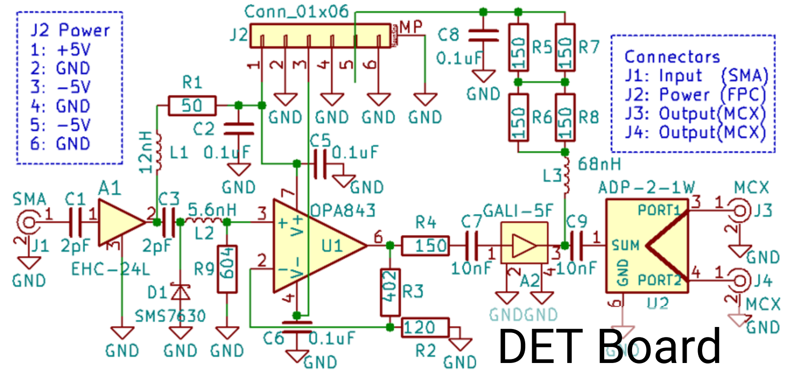
- A lower frequency, two waveguide assembly will be used on the PFRC device, due to its significantly lower density plasmas
- The two horns will be placed on adjacent ports, viewing the plasma through lexan windows

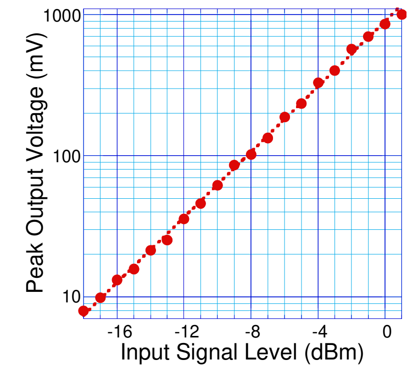
Key USPR Subsystems (Transmitter and TOF Electronics) Completed

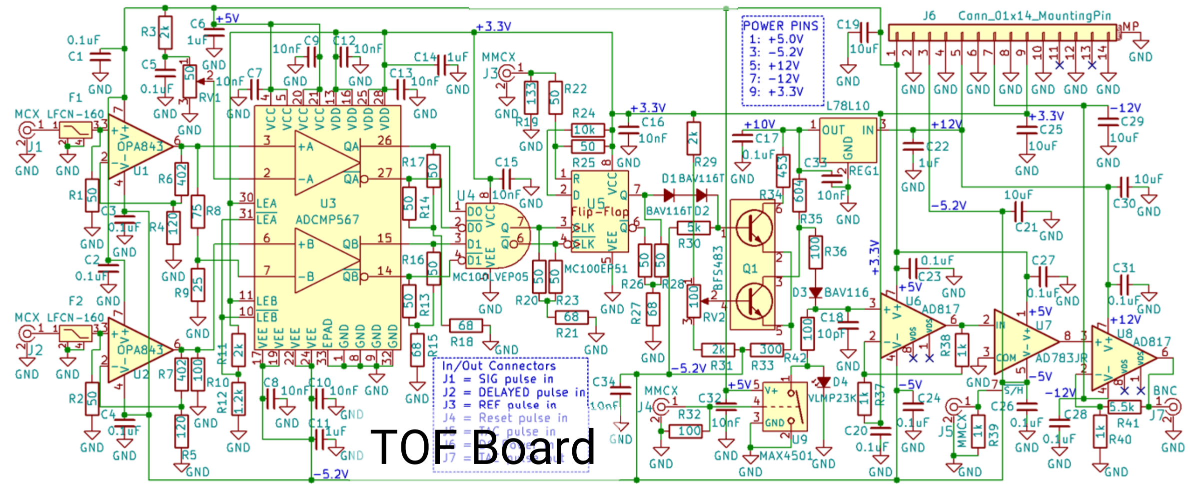


USPR Transmitter

- A 110 cm length of WRD475 waveguide stretches a 5V, 65 psec FWHM impulse signal into a 4.5 nsec chirp spanning 5.0 to 9.5 GHz
- The low frequency chirp is amplified, frequency doubled, and then amplified once more to form the 10 to 19 GHz baseband chirp shown above







USPR Time-of-Flight (TOF) Electronics

- Amplified high-speed detector boards developed for 2-12 GHz (see above, top) and for 8-18 GHz
- Customized time-of-flight electronics boards developed (see above, bottom)

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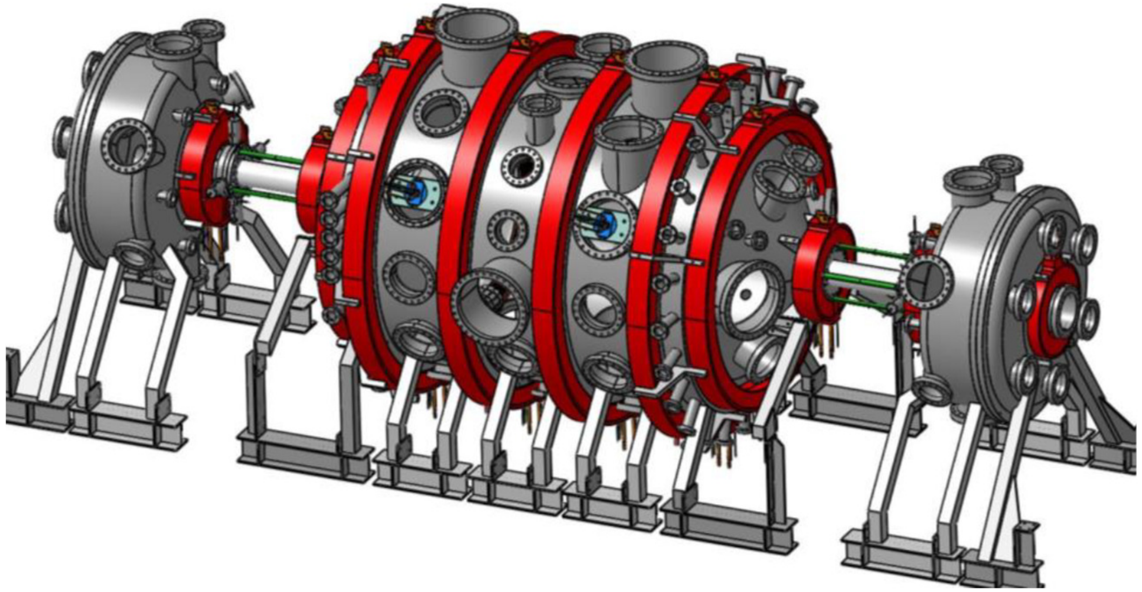
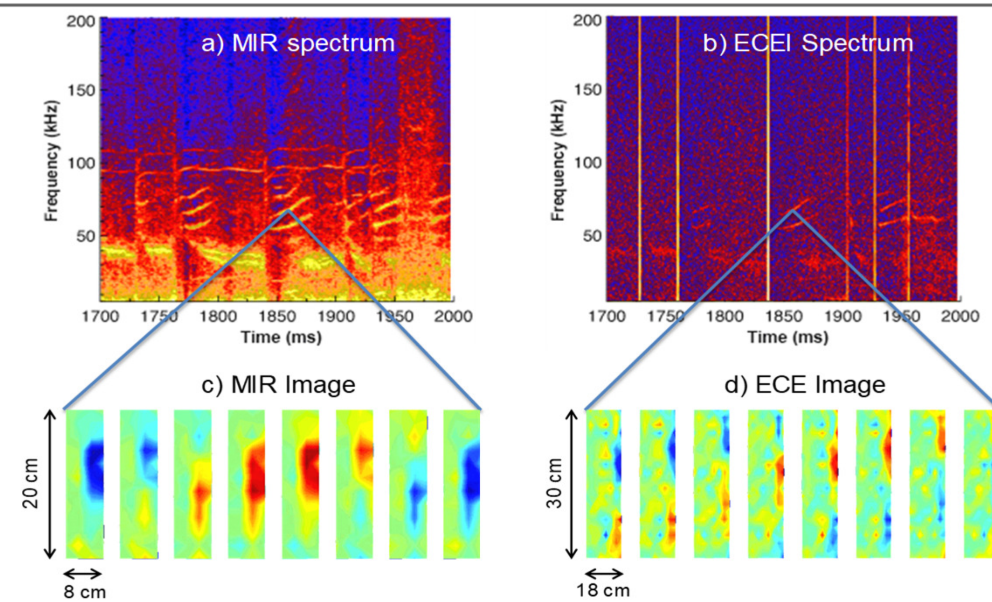
Future Plans for USPR Beyond ARPA-E Funding, and Opportunities to Provide Millimeter-Wave Diagnostic Support to ARPA-E and Others





- A non-disclosure agreement has been signed with Lockheed Martin CFR in preparation for a possible test on their device
- Originally planned for after testing is complete on the two ARPA-E funded devices; this could take place first depending on COVID-19 travel restrictions as laboratory testing comes to a close

- UC Davis has an active program in millimeter-wave and THz diagnostics available to ARPA-E and others in the magnetic fusion plasma community
  - Electron cyclotron emission (ECE) imaging for 2-D time-resolved T_e fluctuations
  - Microwave imaging reflectometry (MIR) for 2-D time-resolved low-k n_e fluctuations
  - Collective scattering for high-k n_e fluctuations
  - Interferometry for chord-averaged n_e measure-ments and real-time density feedback control

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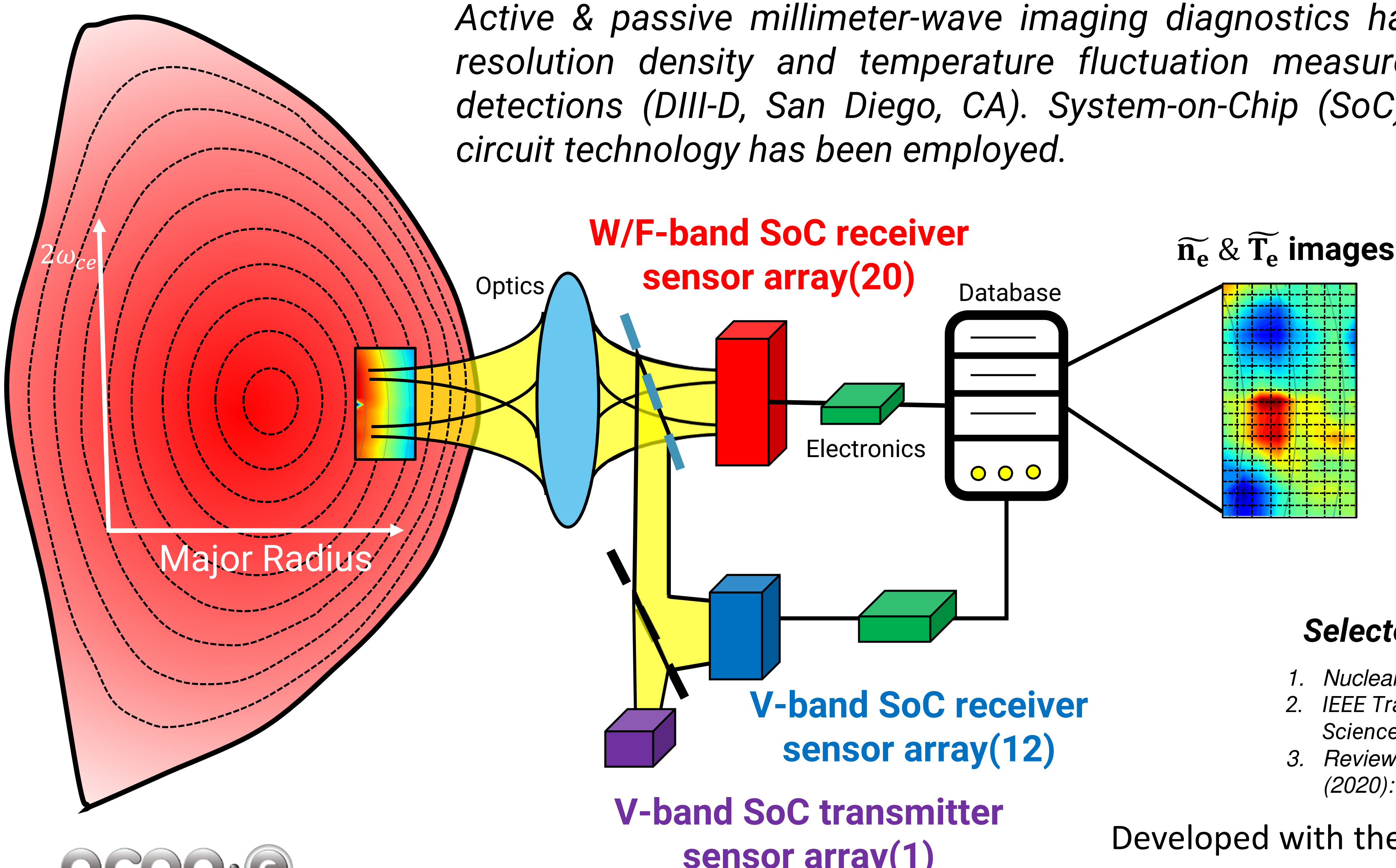
Opportunities to Provide Millimeter-Wave Diagnostics

Active & passive millimeter-wave imaging diagnostics have been developed for high resolution density and temperature fluctuation measurements by phase/amplitude detections (DIII-D, San Diego, CA). System-on-Chip (SoC) millimeter wave integrated circuit technology has been employed.



High resolution images:

- *cm and μs resolution*
- *Temperature fluctuation*
- *Absolute temperature*
- *Density fluctuation*

Selected References

1. *Nuclear Fusion 57.7 (2017): 072007*
2. *IEEE Transactions on Plasma Science* 47.5 (2019): 2110-2130.
3. *Review of Scientific Instruments 91.9 (2020): 093504. [Editor Pick]*

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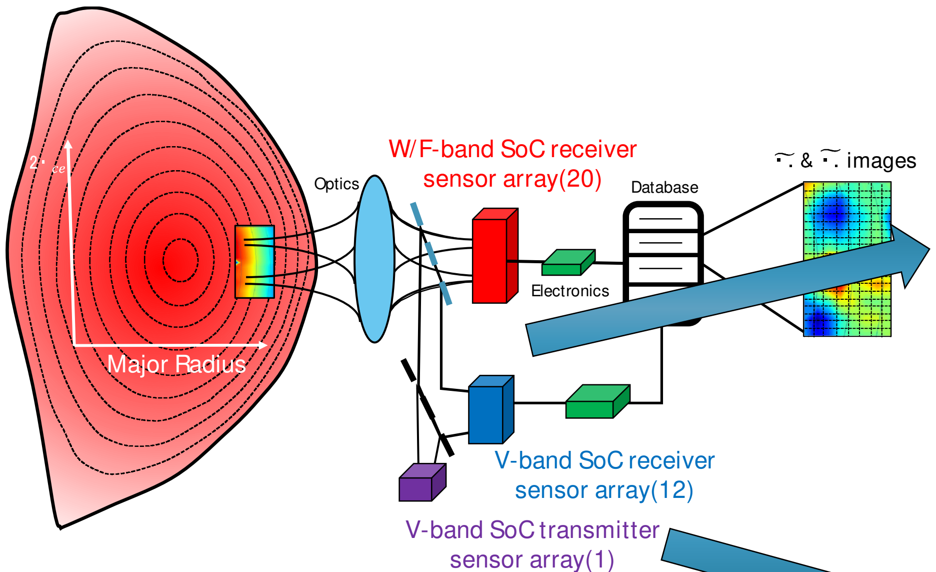
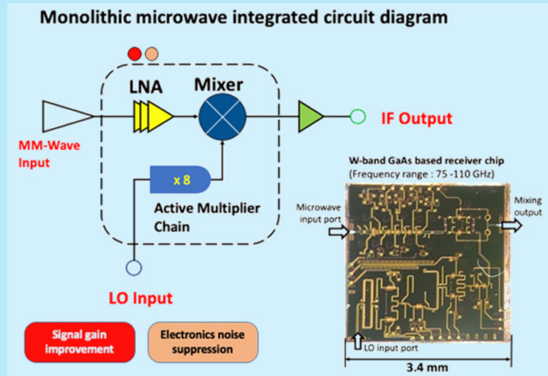
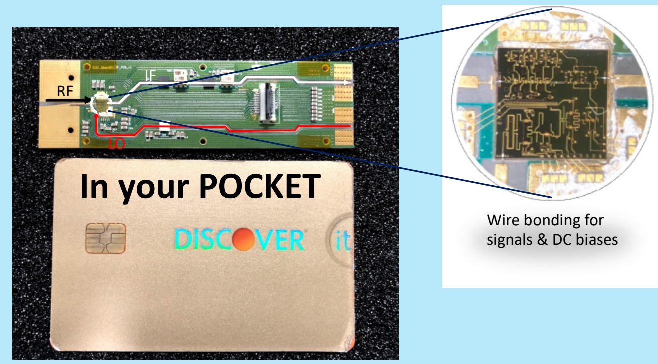
Opportunities to Provide Millimeter-Wave Diagnostics

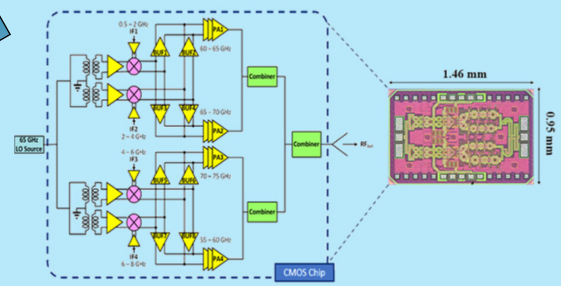




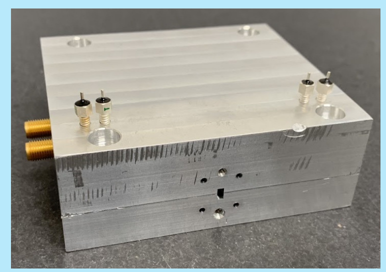
Receiver chip diagram



Portable receiver module



Transmitter chip diagram



Transmitter chip enclosure

- The SoC approach has been developed and successfully applied on high temperature plasma diagnostics, with wide working frequency bands from 55 to 140 GHz.
- The landmark improvements include, enhanced SNR, noise suppression, shielding, reduced complexity, compact size, ability to operate in harsh environments, and cost reduction.
- The SoC approach enhances the measurements' capabilities on MHD instabilities, turbulence behavior during ELM suppression, and magnetic islands.

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